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# A review on exergy analysis of vapor compression refrigeration system

J.U. Ahamed*, R. Saidur, H.H. Masjuki

*Department of Mechanical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia*

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ABSTRACT

This paper reviews on the possibilities of researches in the field of exergy analysis in various usable sectors where vapor compression refrigeration systems are used. Here, it is found that exergy depends on evaporating temperature, condensing temperature, sub-cooling and compressor pressure. It also depends on environmental temperature. Nowadays, hydrocarbons are considered as refrigerant having low ODP and GWP, and these are considerable in the aspect of exergy analysis. Refrigerants R 407a, R 600a, R 410a and R 134a are considered and analyzed with respect to exergy efficiency. Mixtures of hydrocarbons with R134a also show better performance with respect to other refrigerants. Among the components of the vapor compression system, much research showed that major part of exergy losses is occurred in the compressor. Nanofluid and nanolubricant cause to reduce the exergy losses in the compressor indirectly.



**Contents**



## 1. Introduction

After the second half of the twentieth century, the industrial revolution increased the utilization of the new technological products in our daily life. This caused more consumption of the energy and made it an inseparable part of the life. Moreover, the rate of energy consumption per capita has become a criterion of success in the development of the countries. Providing the growing society with the energy ceaselessly, safely and sufficiently, it is necessary to have an increasing amount of productivity and activity in this area. Currently, it is possible to identify three policy themes related to the energy. These are [1]:

- the traditional energy policy agenda relating to security of energy supply;
- the environmental impact of energy, its production, transformation and use, and
- the trend towards liberalization and enhancement of competition in energy markets, notably in the electricity and gas sectors.

This situation led the scientists to develop the cycling ways of the energy and to get more efficiency from the energy sector. For

* Corresponding author.
*E-mail address:* jamal293@yahoo.com (J.U. Ahamed).

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the improvement of the systems, two methods are illustrated viz. energy and exergy analysis.

The energy balance is a basic method of any process investigation. It makes the energy analysis possible, points at the needs to improve the process, is the key to optimization and is the basis to develop the exergy balance. Analysis of the energy balance results would disclose the efficiency of energy utilization in particular parts of the process and allow comparing the efficiency and the process parameters with the currently achievable values in the most modern installations. They will establish also the priority of the processes requiring consideration, either because of their excessive energy consumption or because of their particularly low efficiency.

For these reasons, the modern approach to process analysis uses the exergy analysis, which provides a more realistic view of the process. The exergy analysis is the contemporary thermodynamic method used as an advanced and useful tool for engineering process evaluation [2,3]. Whereas, the energy analysis is based on the first law of thermodynamics, and the exergy analysis is based on both the first and second laws of thermodynamics. Both analyses utilize also the material balance for the systems considered.

Thermodynamic processes in vapor compression refrigeration systems release large amounts of heat to the environment. Heat transfer between the system and the surrounding environment takes place at a finite temperature difference, which is a major source of irreversibility for the cycle. Irreversibility causes the system performance to degrade. The losses in the cycle need to be evaluated considering individual thermodynamic processes that make up the cycle. Energy (first law) analysis is still the most commonly used method in the analysis of thermal systems. The first law is concerned only with the conservation of energy. It does not provide information on how, where, and the amount of performance is degraded. As a complement to the present materials and energy balances, exergy calculations can provide increased and deeper insight into the process, as well as new unforeseen ideas for improvements [4]. Dincer [5] reported the relationship between energy and exergy, exergy and the environment, energy and sustainable development, and energy policy making details. Exergy analysis is a powerful tool in designing, optimization, and performance evaluation of energy systems. The principles and methodologies of exergy analysis are well-established [6–10]. An exergy analysis is usually aimed to determine the maximum performance of the system and to the sites of exergy destruction [11].

Exergy analysis of a complex system can be performed by analyzing the components of the system separately. Identifying the main sites of exergy destruction shows the direction for potential improvements. An important objective of exergy analysis for systems that consume power such as refrigeration, liquefaction of gases, and distillation of water is finding the minimum power required for a certain desired result [12,13]. There have been several studies on the exergy analysis of refrigeration and heat pump systems [14–21]. Leidenfrost et al. [21] investigated performance of a refrigeration cycle using Freon-12 as the refrigerant based on the exergy analysis. Akau and Schoenhals [17] studied a heat pump system experimentally that uses water as the heat source and heat sink. Kaygusuz and Ayhan [19] presented the experimental results of the exergy analysis of a solar assisted heat pump system. They investigated the effects of various parameters on the system performance. Torres-Reyes et al. [14,20] also studied a solar assisted heat pump experimentally, and optimized the system using exergy analysis. Chen et al. [18] studied the optimization of a multistage nonreversible combined refrigeration system. Kanoglu [12] presented a methodology for the exergy analysis of multistage cascade refrigeration cycle and obtained the minimum work relation for the liquefaction of natural gas. The conventional view expressed by Strobridge [22] that the exergy efficiency of the actual refrigeration cycles does not depend on the refrigeration temperature was questioned by Bejan [15]. Author showed that the exergy efficiencies decrease as the refrigeration temperature decreases. He offered two simple models to explain this trend. In his models, thermodynamic imperfections are explained largely by the heat transfer irreversibility.

In this paper, exergy analysis is applied to the vapor compression refrigeration cycle. The expressions for the exergy efficiency and exergy loses (lost works) and pressure losses for the individual processes that make up the cycle as well as the coefficient of performance (COP) and second law efficiency for the entire cycle are analyzed. Effects of condensing and evaporating temperatures on the exergy losses, pressure losses, second law efficiency, and COP are investigated. In many vapor compression systems, it is shown that refrigerants and lubricants mixture is the factor for performance. For global warming problem and ODP, hydrocarbons are used as a refrigerant and mineral oils are their lubricant. Different hydrocarbon mixtures are tested in the different experiments. However, still now there is no unique solution for that concern. More analysis is necessary to have a concluded decision for refrigeration system. Vapor compression refrigeration systems are widely used in the refrigerators and air conditioning system. Air conditioning systems are also different according to their purposes. So, their refrigerants may be different. But everywhere, energy as well exergy analysis is necessary to achieve greater output and system with high performance.

The main objective of the present study is to evaluate and analyze the energy use and its efficiency by reviewing the studies conducted on various countries or societies. Thermodynamic relations are used to perform energy and exergy analyzes of countries. The classification of studies conducted and the approaches applied are then investigated in terms of subsectors, such as utility, industrial, residential–commercial, and transport sectors. Finally, it concludes that exergy analysis is essential for vapor compression system.

## 2. Background of the study

The energy performance of HVAC systems is usually evaluated based on the first law of thermodynamics. However, compared to energy analysis, the exergy analysis can better and accurately show the location of inefficiencies. The exergy method is a relatively new technique in which the basis of evaluation of thermodynamic losses follows the second law rather than the first law of thermodynamics. The results from exergy analysis can be used to assess and optimize the performance of HVAC systems. From the study of Saidur et al. [4], it has been found that major exergy losses have been caused in the refrigerator – freezer followed by air conditioner, washing machine, fan, rice cooker, iron, VCD/VCR/DVD player, and about 21% of total losses are caused by the refrigerator-freezer and 12% of the total losses are caused by the air conditioner. So, it indicates that a major part of exergy losses in the energy sector is caused in the vapor compressor system (refrigerator and air conditioner, 33%). Exergy analysis that is applied to a system describes all losses in the system components and the whole system. With the use of irreversibility, it is more helpful in determining the optimum operating conditions [23]. In addition, integration of energy, entropy and exergy analysis can present a whole picture of the system performance. A number of applications of exergy analysis in HVAC system have shown its effectiveness. Kanoglu et al. [24] analyzed an experimental open-cycle desiccant cooling system and showed that the desiccant wheel has the greatest percentage of total exergy destruction followed by the heating system. Ren et al. [25] evaluated the performance of evaporative cooling schemes and showed that the regenerative evaporative cooling has the best performance, and the effectiveness of indirect evaporative heat exchange has

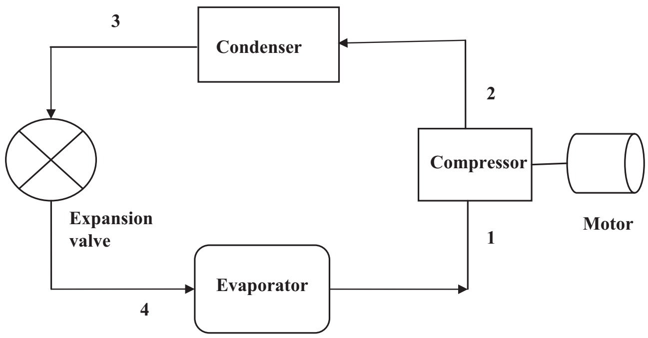


**Fig. 1.** Schematic diagram of vapor compression refrigeration system.

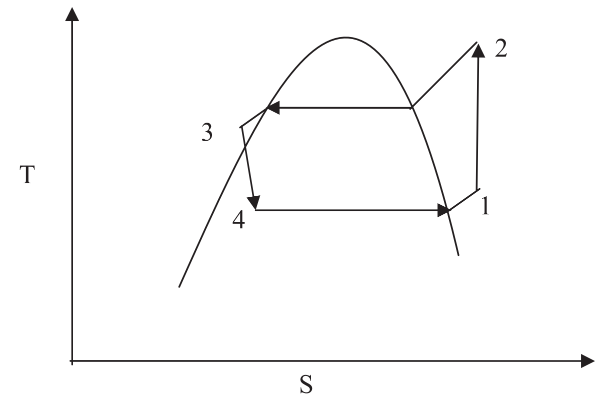


**Fig. 2.** *T–S* diagram of vapor compression refrigeration system.

great importance in improving the exergy efficiency of a regenerative scheme. Asada and Takeda [26] found that the ceiling radiant cooling system with well water is not exergy efficient because of its relatively large electricity consumption by pumps. Badescu [27] found that in a vapor compression heat pump, most exergy losses occur during the compression and condensation process. Rosen et al. [28] expressed the opinion that one major weakness in the building energy analysis is the lack of using the second-law analysis. Major analyses are conducted with energy performance of hydrocarbons as a refrigerant. In order to choose the refrigerant exergy analysis should be needed. According to 1st and 2nd law analyses, we should select the refrigerant for the vapor compression refrigeration system. It is also necessary to know the optimum operating conditions.

## 3. Theoretical formulation for vapor compression system

Energy and exergy analyses need some mathematical formulations for the simple vapor compression refrigeration cycle. In the vapor compression system, there are four major components: evaporator, compressor, condenser, and expansion valve. External energy (power) is supplied to the compressor and heat is added to the system in the evaporator, whereas in the condenser heat rejection is occurred from the system. Heat rejection and heat addition are dissimilar to different refrigerants, which cause a change in energy efficiency for the systems. Exergy losses in various components of the system are not same. A temperature and pressure are denoted by $T_0$ and $P_0$, respectively. Exergy is consumed or destroyed due to entropy created depending on the associated processes [29]. To specify the exergy losses or destructions in the system, thermodynamic analysis is to be made. In this study, the following assumptions are made:

1. Steady state conditions are remained in all the components.
2. Pressure loses in the pipelines are neglected.
3. Heat gains and heat loses from the system or to the system are not considered.
4. Kinetic and potential energy and exergy losses are not considered.

Schematic diagram of a simple vapor compression refrigeration system is shown in Fig. 1 and the relevant *T–S* diagram of the system is shown in Fig. 2. In the diagram, *s* 1–2 is isentropic compression in the compressor. The other states viz. 2–3, 3–4 and 4–1 show condensation, throttling in the expansion valve and evaporation in evaporator respectively.

Mathematical formulation for exergy analysis in different components can be arranged in the following way [30]:

Specific exergy in any state,

$$\text{Specific exergy in any state,}\quad \Psi = (h - h_0) - T_0(s - s_0) \tag{1}$$

*For evaporator*:

$$\text{Heat addition in evaporator,}\quad Q = \dot{m}(h_1 - h_4) \tag{2}$$

$$\text{Exergy destruction,}\quad I_{ev} = \dot{m}(\psi_4 - \psi_1) + Q\left(1 - \frac{T_0}{T_{ev}}\right)$$

$$I_{ev} = \dot{m}[(h_4 - h_1) - T_0(s_4 - s_1)] + Q\left(1 - \frac{T_0}{T_{ev}}\right) \tag{3}$$

*For compressor*:

$$\text{Compressor work,}\quad W_c = \dot{m}(h_2 - h_1) \tag{4}$$

$$\text{For non}-\text{isentropic compression,}\quad h_c = \frac{h_{2s} - h_2}{\eta_c} \tag{5}$$

$$\text{Electrical power,}\quad W_{el} = \frac{W_c}{\eta_{mech} \times \eta_{el}} \tag{6}$$

$$\text{So, exergy loss,}\quad I_{comp} = \dot{m}(\psi_1 - \psi_2) + W_{el} = \dot{m}[(h_1 - h_2) - T_0(s_1 - s_2)] + W_{el} \tag{7}$$

*For condenser*:

$$Q_{cond} = \dot{m}(h_2 - h_3) \tag{8}$$

$$\text{Exergy loss,}\quad I_{cond} = \dot{m}(\psi_2 - \psi_3) - Q_{cond}\left(1 - \frac{T_o}{T_{cond}}\right)$$

$$= \dot{m}(h_2 - h_4) - T_0(s_2 - s_3) - Q_{cond}\left(1 - \frac{T_o}{T_{cond}}\right) \tag{9}$$

*For expansion valve*: energy destruction,

$$I_{\exp} = \dot{m}(\psi_4 - \psi_3) = \dot{m}(s_4 - s_3)\,[\text{Throttling},\ h4 = h1] \tag{10}$$

$$\text{Coefficient of performance,}\quad COP = \frac{Q_{ev}}{W_{el}} \tag{11}$$

Total destruction,

$$I_{total} = I_{cond} + I_{\exp} + I_{comp} + I_{evap} \tag{12}$$

Exergy efficiency.

$$\eta_x = \frac{\psi_1 - \psi_4}{W_{el}} \tag{13}$$

Energy efficiency ratio

$$EER = \frac{\text{Energy out}}{\text{Work of Compression}} = \frac{h_1 - h_4}{W_{el}} \tag{14}$$

With reference to cited literatures, it is assumed that mechanical efficiency of the compressor is 90% and the electrical efficiency of the motor is 90%.

## 4. Exergy analysis for components of the refrigeration system

Vapor compressor refrigeration systems are used in refrigerator and air conditioning systems. In both cases same cycles are used. But the application fields are different. So sometimes, different kinds of refrigerants are used. All the vapor compression refrigeration systems consist of condenser, evaporator, expansion valve or throttling valves and compressor. In the refrigeration system, coefficient of performance is varied with the change in refrigerants or the evaporator and condenser. Irreversibilities are different in the different components of the vapor compression system. The losses in a component should be measured to improve the performance of the whole system. The losses in the cycles need to be evaluated considering individual thermodynamic processes that make up the cycle. It is found that most of the irreversibility occurs in the compressor parts. Changes of the evaporator temperature also change exergy losses. If the temperature difference is high the irreversibility also high, and it can be decreased by staging the compression [31].

Exergy loss increases as the temperature of the evaporator decreases. This can be explained that if the evaporating temperature increases the heat transfer between the refrigerant entered into the evaporator tubes and the medium being cooled also increases, which ultimately increase the refrigerating effect thus the exergy loss decreases. Among the three refrigerants, isobutene exhibit minimum exergy loss [32]. Exergy losses in the individual components for Refrigerant R-600a are explained in that article with the variation of evaporating temperatures. The trends of exergy losses in the different components of the vapor compression system for other refrigerants are also found similar. A greater portion of exergy losses takes place in the compressor. Evaporator has lower exergy losses compared to the other components. Experimental results with other refrigerants also show the similar results i.e. compressor has the highest exergy losses compared to that of other components. The exergy losses in the components decrease with the increase of evaporating temperature. The higher the temperature differences in any component with the surroundings, the higher the exergy loss. Bayrakci and Ozgur [30] studied about four different pure hydrocarbons (R290), butane (R600), isobutene (R600a) and isopentane (R1270) and also R22 and R134a. The authors found that R600 can be assumed as an appropriate alternative to R22 and R134a. Yumrutas et al. [33] studied the effect of evaporating and condenser temperature on exergy loss (lost work).

Much research is done to find the exergy destruction in the different components of the vapor components with different refrigerants. The efficiency defects in the compressor, condenser, throttle vale and evaporator are explained by Arora and Kaushik [34]. The authors showed the exergy efficiency of the different components. The worst component from the viewpoint of irreversibility or exergy destruction is a condenser followed by compressor, throttle valve and evaporator, respectively. It is apparent that the most efficient component of the vapor compression system is liquid vapor heat exchanger (2–8.5%). Kabul et al. [35] studied the energy and exergy analysis for vapor compression system with refrigerant R600a at specified operating conditions. Author studied using computer software for a system of refrigeration capacity 1 kW. They found that irreversibility is higher in the condenser compared to that in the evaporator. The reason is that the refrigerant undergoes almost an isothermal heat addition process during phase change in the evaporator with a relatively small temperature difference between the evaporator and the cold space [33]. However, in the condenser only part of the heat rejection takes place during the phase change process with a large temperature difference between the condenser and outside air. But the compressor shows higher irreversibility (37.87%) compared to the other components due to non-isentropic compression. Irreversibility in the expansion valve (11.27%) also was higher than that in evaporator (9.83%) due to pressure drops occurred in the expansion valve. Internal heat exchanger (1.87%) has the lowest irreversibility among the components as no heat transfer to or from the system was occurred [35].

Harrell [36] showed in his experiment that the next largest component of exergy destruction was found to be the refrigeration systems. Author found that the compressors were the main sources of this loss, and that the West compressor had losses nearly 50% greater than those of the South compressor at high loads. However, both refrigeration systems had a peak exergy efficiency of approximately 30%, slightly higher for the West system, and dropping to <10% at low loads. He also found that heat transfer irreversibility in the evaporator were approximately 20% of the refrigeration system losses in the South system, but only 10% in the West system. These ratios were nearly constant over the range of modeled loads. The reduced losses of the West system can be attributed to the 3-pass evaporator versus the 2-pass evaporator at the South chiller. This difference is also reflected in the exergy unit cost increases due to the evaporators. The evaporator is responsible for about 40% of the cost of the refrigeration system at the South chiller, but only 20% of the cost at the West chiller, where the compressor is a more significant cost component.

Hepbasli [37] applying EXCEM method for the household refrigerators found that the greatest irreversibility occurred in the compressor, followed by the condenser, capillary tube, evaporator and superheating coil. The test was conducted in accordance with EN 28187 [38]. The refrigerant was R134a and R600a. Shilliday et al. [39] tried to make an energy and exergy analysis of R744, R404A and R290 refrigeration cycles in the different components at various condensing and evaporating temperatures. This study aims to identify the worst performing components in a transcritical R744 cycle and indicate how the exergy destruction in the cycle can be decreased by introducing variations to the basic cycle. The EES software was used as the basis for the thermodynamic analysis of the cycles and system components[40]. At the 25 °C condensing temperature, the expansion valve for the R744 contributes the highest percentage exergy ratio, an average of 25%, compared with 14% and 12.5% for R404A and R290, respectively. For R404A and R290, the compressor was the worst performing component at 25 °C condensing temperature, both having exergy ratios of 24% (Table 1).

## 5. Basic steps for development of the system

We know that COP and exergy efficiency of a vapor compression can be increased by subcooling. It is evident that sub-cooling increases cooling capacity whereas there is no changes in compressor work, hence COP increases. Analysis shows that increase in COP reduces the exergy destruction ratio (EDR) and increases exergy efficiency. From the analysis of Arora and Kaushik [34], it is found that exergy efficiency for 10 °C sub-cooling is 14.9% for R404 and 14.8% for R507 at 40 °C condenser temperature. With the increase in drop in pressure in evaporator and condenser COP and exergy efficiency reduce whereas EDR decreases. Using computer program for any refrigerant, Adegike et al. [41] also found that sub-cooling up to 2–5 °C is advantageous for energy and exergy performance of a refrigeration system but superheating is not advantageous. In their works, simple calculation methods based on empirical formulae [42] for simple refrigeration system were used. Second law efficiency and the coefficient of performance (COP) were increased and the total exergy losses were decreased with the decrease in temperature difference between the evaporator and

**Table 1**
Exergy destruction rate (EDR) in the components of the vapor compression system.

| Refrigerants | Authors | Analysis | Exergy losses ED in the components | Reason/explanation |
|---|---|---|---|---|
| R744 | Yumrutas et al. [33] | Computational analysis | Most of the loss occurred in the compressor, then in the condenser, expansion valve and evaporator. | Due to only phase change in the evaporator and having less temperature difference exergy loss is minimum. |
| R134a, R600a | Hepbasli [37] | EXCEM method | Greatest irreversibility was occurred in the compressor, followed by the condenser, capillary tube, evaporator and superheating coil. | Compressor efficiency was found 52% so the loss was maximum in the compressor. Also superheating caused more exergy losses. |
| R600a | Kabul et al. [35] | Using EES software. Its a computational Program | Exergy looses were high in the condenser (20.75%) compared to those in the evaporator (9.83%) but highest losses were occurred in the com pressor (37.87%). | This analysis was only for R600a and internal HX was used there. |
| R744, R404A and R290 | Shilliday et al. [39] | Computationa, EES software | Exergy losses in the expansion valve for R744 is higher in case of condensing temperature 25 °C but for R290 and R404A it is higher in the compressor. | Proper staging and sub-cooling can reduce the exergy losses in the components. |

the refrigerated space and between the condenser and outside air [33].

## 6. Effect of refrigerant on exergy analysis/parameters

Many researches were conducted about energy performance of the vapor compression system. It is found that refrigerant has great effect on energy performance. Among the refrigerants, R12 was used as a refrigerant in refrigerator and R-22 was used in air conditioner having higher COP compared to that of others used as a refrigerant. But according to Montréal Protocol both R-12 and R-22 having higher global warming potential should be phased out. Considering the global warming potential and green house effect CFCs and HCFCs are to be replaced. HFC was considered as a replacement of CFC and HCHC. But HFC 134a was not miscible with the existing lubricant, mineral oil (MO). Lubricant should be changed and it has been found that POE is suitable for HFC 134a and modification of the whole system is necessary. Besides, HFC 134a has high global potential compared to hydrocarbon and their mixtures. Another thing is that, POE is not available and HFC 134a is hygroscopic. Unfortunately, the radiation properties of HFCs like R134a make them powerful global warming agents. So, performance is also decreased. Hence the researchers tried to find a suitable refrigerant for a long time to meet the Montréal protocol and performance also. Hydrocarbons are the refrigerants which also high latent heat of vaporization. So, now a day, it is considered as research interest to find the performance of HC and their mixtures as refrigerant compared to that of HCFC 134a and HFC 22. Wongwises and Chimres [43] studied that the hydrocarbon (propane/butane 60%/40%) is suitable refrigerant compared HFC134a for a number of reasons. Firstly, the refrigerator in their experiment used less energy than the refrigerator used using HFC134a. This is because the saturation temperature of propane/butane is lower and the latent heat of vaporization of propane/butane is higher than those of FHFC 134a. As the hydrocarbons have higher latent heat value and lower evaporator temperature so it causes less exergy destruction. Thus on the basis of second law efficiency hydrocarbons are suitable. Alsaad and Hammad [44] have examined the performance of a domestic Refrigerator using propane/butane mixture for a possible replacement of R12. A comparative study is presented for different pure HCs propane (R290), butane (R600), isobutene (R600a), isopentane (R1270) and also R22 and R134a with theoretical analysis. This was a comparative study about energetic and exergy performance [30]. The energetic and exergy efficiency reaches maximum for R1270 at all working conditions. However the same efficiencies all were obtained with R600.

Coefficient of performance (COP), exergy destruction (ED) and exergy efficiency of refrigerants R-22, R-407C and R-410A have been predicted with the help of a developed computational model [45]. The present investigation has been carried out for evaporator and condenser temperatures in the range of −38 °C to 7 °C and 40 °C to 60 °C, respectively. The results indicate that COP and exergy efficiency for R-22 are higher in comparison to R-407C and R-410A. The optimum evaporator temperature for minimum ED ratio has been evaluated at various condenser temperatures. Aprea and Greco [46] found from an experiment that R-407 would not be a substitute of R-22 for air conditioning system on the basis of exergy analysis. Exergy losses for refrigeration cycle in the industrial natural gas liquefaction plant using Refrigerants propane, ethane and methane were examined by Mehrpooya et al. [48]. The results indicate that largest exergy loss occurred for ethane as refrigerant. From this paper it can be concluded that the exergy analysis of NGL (Natural gas liquids) propane refrigeration cycle can be applied to the other actual cycles like LNG (LNG exchanger) refrigeration cycles. On the basis of exergy analysis within some mixtures for a cascade system at low temperature, Somasundaram et al. [47] found that ARC system with R23/R290 mixture, showed less exergy loss in comparison to R125/R600 and R23/R600 mixtures. Authors selected the refrigerants on the basis of higher differences in boiling points among the refrigerants in order to have effective phase separation (Table 2).

Shilliday et al. [39] tried to make an energy and exergy analysis of R744, R404A and R290 refrigeration cycles. To date it is generally accepted that a transcritical R744 system has a lower COP compared with a R-404A system [39]. In this paper a comparative exergy and energy analysis is preformed on transcritical R744 cycles for commercial refrigeration use and compared with R-404A and the Hydrocarbon R-290. In that analysis, R290 displayed the lowest exergy destruction ratio whereas, R744 displayed the highest exergy destruction ratio.

## 7. Effect of evaporating temperature on exergy losses

The exergy destructions were measured for the vapor compression refrigeration system. The liquid refrigerant at low pressure side enters the evaporator. As the liquid refrigerant passes through the evaporator coil, it continually absorbs heat through the coil walls which causes the medium to cool. During this, the refrigerant continues to boil and evaporate. Finally the entire refrigerants become evaporated and only vapor refrigerant remains in the evaporator coil. The liquid refrigerant still colder than the medium being cooled, therefore, the vapor refrigerants continue to absorb heat. Exergy loss increases as the temperature of the evaporator decreases as shown in Fig. 3. This can be explained

**Table 2**
Effects of refrigerant on exergy losses for vapor compression system.

| Objectives | Comparison | Results | Reference | Comments |
|---|---|---|---|---|
| Exergy analysis | R22 and R407 | Irreversibly in the compressor is high | Aprea and Greco [46] | R-407 would not be a substitute of R22 on the basis of exergy efficiency |
| Theoretical analysis of vapor compression system | R 502, R404 and R507 | Exergy efficiency of R507 is better compared to the other refrigerants | Arora and Kaushik [34] | With condenser temperature 40–550 °C |
| Energy and energy analysis of pure hydrocarbons | R290, R600, R600a, R1270, R22 and R134a | R1270 showed better energy and exergy efficiency, R600 also same efficiency | Bayrakci and Ozgur [30] | It's a theoretical analysis based on EES package program |
| Thermodynamic analysis of vapor compression analysis | R134a, R12, R502 | R 134a showed better performance on the basis of 2nd law efficiencyand interstaging is better than single staging | Khan [31] | It a MS thesis and comparison |
| To find the COP, exergy efficiency and exergy destruction | R-22, R-407C and R-410A | COP and exergy efficiency of R22 is higher compared to others | Arora et al. [45] | This is also based on computational program |
| Exergy based Refrigerant selection | Three mixtures: R23/R290, R23/R600,R12 5/R600 | Less exergy loss with R23/R290 in comparison with R125/R600 and R23/R600 mixtures | Somasundaram et al. [47] | Its an auto simulation process and applicable for low temperature. Difference in Boiling points of the mixtures is high |

that if the evaporating temperature increases the heat transfer between the refrigerant entered into the evaporator tubes and the medium being cooled also increases which ultimately increase the refrigerating effect thus the exergy loss decreases. Among the three refrigerants, isobutene exhibits minimum exergy loss [32].

At higher evaporating temperature, exergy loss is lower compared to that of at lower evaporating temperature. Vincent and Heun [49] found that higher exergy destruction occurred in the compressor compared to condenser and other parts. They found that compressor has greater effect on the total exergy destruction. Energy and exergy analysis has been applied to the vapor compression system for R600a using computer program [35]. The graphics showed that, with the increase in evaporator temperature, the values of COP, efficiency ratio and exergy efficiency were increased, whereas the total irreversibility rate was decreased. It means that an increase in the evaporator temperature affects the system efficiency positively. A computational model based on the exergy analysis was investigated for the effect of evaporating and condensing temperature for refrigerant ammonia [42]. Total exergy losses decreases with the increase of evaporating temperature and an opposite trend exists for the second law efficiency as expected. Kalaiselvam and Saravanan [50] reported that exergy losses decreased with the increase in evaporating temperature. To obtain good second law efficiency and minimum exergy losses the system has to be operated at 4 °C. The refrigerants were R717, R22 and R407C.

## 8. Effect of condensing temperature on exergy losses

Condenser temperature has a great effect on exergy of the vapor compression system. Kabul et al. [35] found that with the condenser temperature, the performance parameters were acted upon oppositely from evaporator temperature. With the increase in condenser temperature, the values of COP, efficiency ratio and exergy efficiency were decreased, whereas the total irreversibility rate was increased. It is shown in Fig. 4 that an exergy loss increases with the increase in condensing temperature for all the refrigerants. It is obvious because higher the temperature difference between the ambient and the component the higher the exergy losses. Availability of work also increased. In the low temperature region, exergy loss for each refrigerant remains same but in the high temperature region the loss for R-600 is increased. Bayrakci and Ozgur [30] also described that exergy losses are higher for higher condensing temperature for R-14a, R22, R-290, R-600a, R600 and R1270. Because the more the difference in temperatures between the ambient (air) and the system (working fluid), the more the exergy losses. Chance of irreversibility increases for temperature rises. From the analysis Jabardo et al. [42], it was found that exergy losses increases with the increase in condensing temperature and an opposite trend exists for the second law efficiency as expected. Kalaiselvam and Saravanan [50] found that for all the refrigerants, exergy efficiency decreased with the increase in condensing temperature. In order obtain a good second law efficiency the system should be operated within the condensing temperature, 35–40 °C.

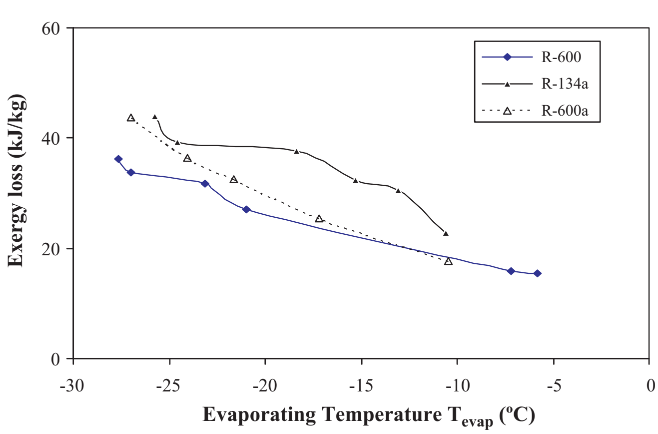


**Fig. 3.** Variation of exergy losses at different refrigerants at different evaporative temperatures.

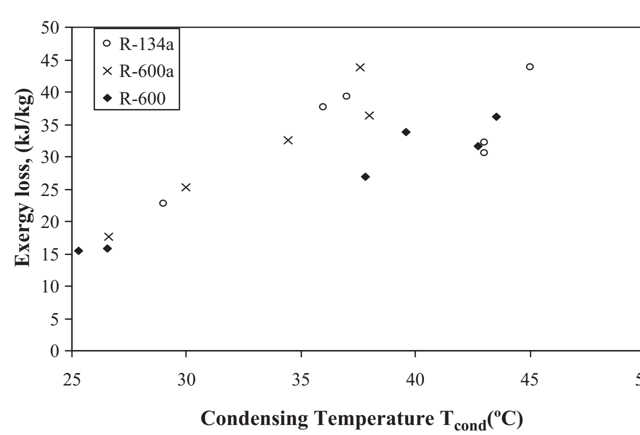


**Fig. 4.** Variation of exergy loss at different condensing temperature with different refrigerants.

## 9. Effect of reference state or dead temperature on exergy losses

Exergy efficiency or exergy destruction also depends on environmental or reference temperature as well system temperatures. A parametric study [37] is conducted to investigate the effect of the varying reference state temperatures on the exergy efficiency of the refrigerator. The Author found that exergy efficiency increases with the increase in reference temperatures. In that study reference temperature varied from 0 to 20 °C. Arora and Kaushik [34] found that with increase in dead state temperature, the term $[1-(T_0/T_r)]$ increases while cooling capacity and compression work remain constant and thus exergy efficiency and exergy destruction reduces. This is justified as exergy efficiency is inversely proportional to EDR. For a fixed condenser temperature, the increase in dead state (reference temperature) causes the irreversibility to decrease and hence EDR and exergy efficiency increases. Both R507 and R404 show the identical trends.

## 10. Effect of lubricant on exergy losses

Lubricant has an effect to reduce the exergy loss in the compressor. Proper lubrication can reduce the frictional losses in the compressor. But another thing is that lubricating oil should be well miscible with the refrigerant. While R-134a is used as a refrigerant POE should be used as lubricant. For hydrocarbons and their blend as refrigerant lubricant should be mineral oil. But there is limited research on exergy with lubricants. Less than 5% oil which is miscible with the refrigerant causes negligible effect in the evaporator or expansion valves. It reduces the frictional losses in the compressor as well reduce the exergy losses in the compressor [51]. The lubricant type and the related oil circulating rates are fundamental for compressor efficiency and strongly affect also the two-phase heat transfer process. One of the most interesting theories was proposed by Kedzierski [52]: a lubricant film is formed in direct contact with the heated surface. The author observed that in presence of small oil mass percentage (typically lower than 0.5% with R134a) the HTC tended to increase, while HTC decreased sharply for higher oil concentrations. So, for low OCR (<0.5%) heat transfer coefficient increases hence mass flow rate of refrigerant is reduced. As a result exergy loss will be reduced.

## 11. Effect of additives on exergy losses

Some researches are found that some additives with high conductivity enhance the heat transfer rate. So, small amount of refrigerant is necessary for creating same refrigerating effect. With the decrease in mass also cause to decrease in exergy. In the other hand for the same refrigerant flow, difference in the operating temperatures will be reduced. Thus it is clear that this temperature reduction will cause to reduce the exergy loss in the whole systems. Copper Oxides (*CuO*), carbon nano-tubes helps to enhance heat transfer. In the field of lubrication, it has been reported that a carbon nano-lubricant might substantially reduce the frictional coefficient with respect to pure oil, which means a better lubricating operation for scroll compressor [53]. Kedzierski and Gong [54] found that a lubricant based nanofluid (nanolubricant) made with a synthetic ester and CuO particles caused a heat transfer enhancement relative to the heat transfer of pure R134a/polyolester (99.5/0.5) of between 50% and 275%. A smaller enhancement was observed for the R134a/nanolubricant (99/1) mixture, which had a heat flux that was on average 19% larger than that of the R134a/polyolester (99/1) mixture. Further increase in the nanolubricant mass fraction to 2% resulted in a still smaller boiling heat transfer improvement of approximately 12% on average. Thermal conductivity measurements and a refrigerant/lubricant mixture pool-boiling model were used to suggest that increased thermal conductivity is responsible for only a small portion of the heat transfer enhancement due to nanoparticles. These results indicate that nanofluid causes a tremendous increase of heat flux as well as thermal conductivity. So less mass flow rate of refrigerant is necessary hence the exergy loss will be decreased with the uses of nanofluid. Jwo et al. [55] discussed the replacement of the R-134a refrigerant and polyester lubricant with a hydrocarbon refrigerant and mineral lubricant. The mineral lubricant included added $Al_2O_3$ as nanoparticles (0.05, 0.1, and 0.2 wt%) to improve the lubrication and heat-transfer performance. Experimental results indicated that the 60% R-134a and 0.1 wt% $Al_2O_3$ as nanoparticles were optimal. So, for small amount of $Al_2O_3$ causes to decrease the mass flow rate of the refrigerant and hence it reduces the exergy loss also.

## 12. System development/conclusions

There are many ways to develop a vapor compression for increasing the exergy efficiency and minimizing the exergy destructions or losses. From the literatures, following steps can help to increase exergy efficiency:

(a) Increasing reference state temperature at an optimum level for comfort and required conditions.
(b) Subcooling up to 5 °C can be introduced for reducing the irreversibility and increasing the system performance.
(c) Staging in compression can be done for reducing the pressure rises in the compressor and hence reduce the irreversibility in the compressor also.
(d) Special care should be taken for the compressor and sealing should be properly done for reducing irreversibility.
(e) Choosing refrigerant having positive evaporative pressure and refrigerant should have high latent heat of vaporization. It helps to reduce the temperature differences between the evaporator and condenser.

## 13. Summary/conclusion

Most of the researches should that maximum exergy loses occurred in compressor among the components of the vapor compressor refrigeration system. Hydrocarbon generally R600a, R410a and R1270 show the best performance according to energy and exergy efficiency of the system. Exergy efficiency can be improved by sub-cooling up to 5 °C and reducing the temperature difference of the evaporating and condensing temperature. It can be increased by increasing reference temperature also. Nanolubricant can reduce the friction coefficient and thus it can increase the exergy efficiency of the compressor. But lubricant should be properly utilized as it cannot deposit in the wall of the evaporator. Nanofluid also can increase the heat transfer performance and it can reduce the mass flow of the refrigerant which indirectly reduces the total exergy losses of the systems. Stages in the compression also can be helpful for reducing compressor power or losses in the compressor.

More researches are necessary to identify the best refrigerant with highest coefficient of performance and highest exergy efficiency to empower the energy savings as well as to reduce the environmental impacts. R-12, R-22 and R134a cannot be used as refrigerant due to their ODP and GWP problems. So, only choice are the hydrocarbons and their blend. But due to flammability issue hydrocarbon cannot be used alone in the industrial sectors. So mixing with some R134a, blend can be a candidate for the industrial purposes. Whereas, more experiments are necessary in order to use nanolubricant and nano fluid and to get the advantages from these

on the basis of exergy analysis. Kalaiselvam and Saravanan [50] found that exergy losses varied with the variation of compressor discharge and suction temperatures. Exergy losses increased with the increase in suction and discharge temperature of the compressor. For better performance of the system, compressor discharge and suction temperature should within 65 °C and 14 °C, respectively.

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